

Mighty Eagle Landers Testbed

AIAA Science and Technology Forum 2015

Kissimmee, Florida

January 5-9, 2015

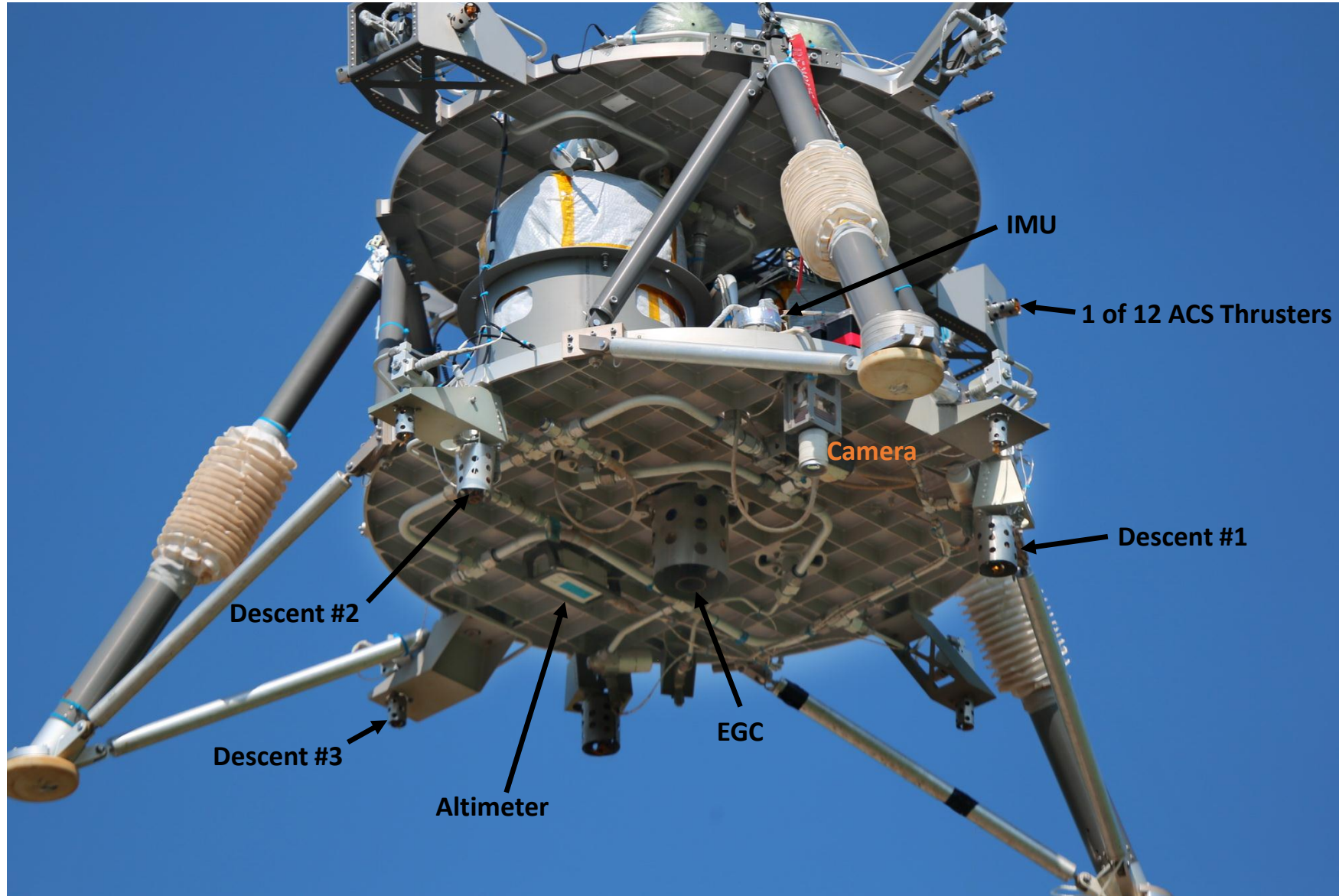


Mighty Eagle Background

- The Mighty Eagle was built as a risk reduction testbed
 - A joint effort by NASA and APL funded by the Robotic Lunar Lander Development Project (RLLDP)
 - Primary objective was to validate the GNC system during final descent (final 50 meters of landing)
 - Secondary objectives included the development of a NASA/APL engineering team, testing the landing legs and testing of optical velocimetry
- Mighty Eagle completed 40 test flights (14 of them tethered)
- Propelled by 90% hydrogen peroxide monopropellant thrusters
 - Propulsion system pressurized with regulated nitrogen
 - A throttled Earth Gravity Cancelling Thruster (EGC) offsets 5/6's the weight of the vehicle during flight
 - The 3 descent and 12 ACS thrusters are all pulsed (on/off)
- Pulsed thrusters are less complex and more reliable than throttled engines
 - Vehicle control with pulsed thrusters presents challenges
 - Pulsed thrusters trade better for small landers
- Physical Characteristics
 - Dry Weight \approx 206 kg, full propellant load \approx 109 kg
- Flight Envelope
 - Max flight time \approx 45 s, max altitude \approx 50 meters, downrange capability \approx 50 m
 - Have ascended @ 6 m/s and translated downrange at 3.5 m/s

Mighty Eagle

http://www.nasa.gov/mission_pages/lunarquest/robotic/



Similitude to a Small Lunar Lander

- The Earth Gravity Canceling (EGC) Thruster is throttled and offsets 5/6's the weight of the vehicle
 - GNC system does not know about the EGC, thinks it is flying in a low-g environment
- FSW runs on a RAD750 computer
 - Similar to the processing power you will have on a space mission
- Software built on the cFE (Core Flight Executive) environment
 - cFE has become a dominant FSW architecture for NASA
 - Used by Mighty Eagle, Morpheus, LRO, RBSP, LRO, LADEE, GPM, ...
 - Under an SAA Moon Express tested control software on the Mighty Eagle
- A Toughbook laptop was installed on the Mighty Eagle and is available to run user supplied algorithms
- Mighty Eagle's configuration ideal for vehicles planning to also use pulsed thrusters
 - A testbed like Morpheus more applicable for vehicles with throttled engines and TVC (Thrust Vector Control)

AR&C Testing

- In 2012 the Mighty Eagle demonstrated Autonomous Rendezvous and Capture
- Using an onboard optical camera (Illunis RMV-4021) AR&C software was added and integrated on the RAD750
 - It was a challenge to “squeeze” AR&C software onto the RAD750
- Successfully identified and flew to the target with AR&C “closing the Loop”



Hazard Avoidance

- In 2013 a commercial stereo camera was integrated onto the Mighty Eagle and a lunar terrain field was built
- Hazard avoidance software required much greater processing performance than the RAD750 could provide
- Installed a Panasonic Toughbook to do the image processing



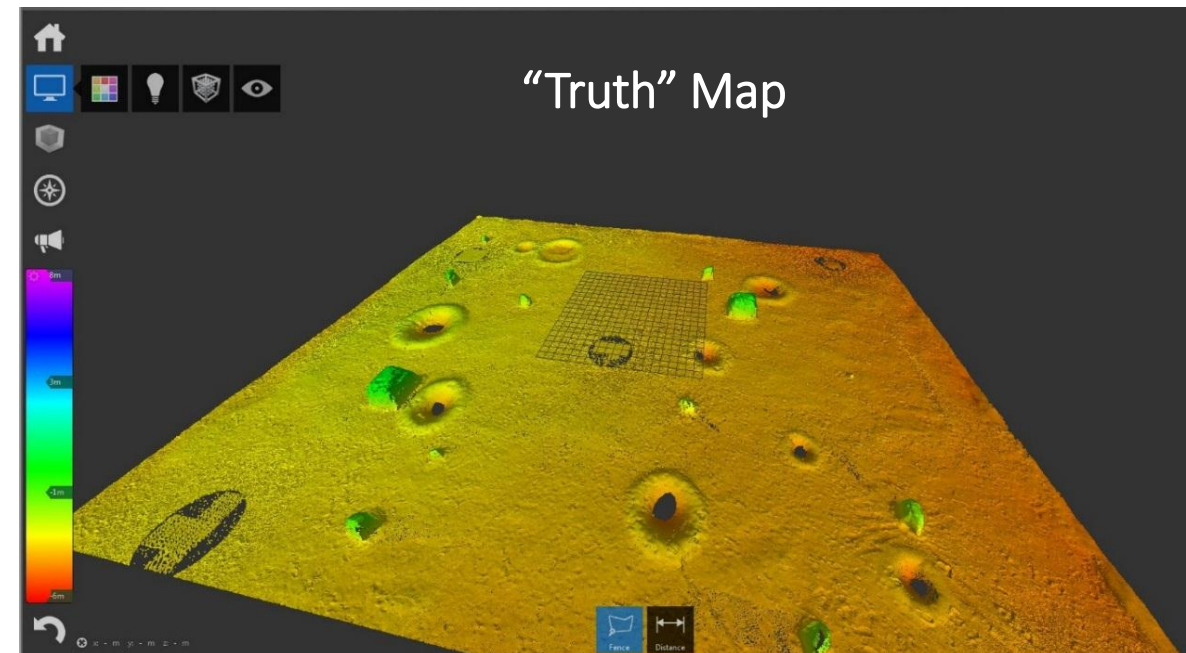
- The Hazard Avoidance flight tests were the first time the cFE software bus was implemented in flight
 - The cFE software bus enabled communication between the RAD750 and Toughbook computers

Lunar Terrain Field



Lunar Terrain Field

- Terrain field covered with ≈ 225 tons of lunar regolith simulant
 - Simulant is crushed volcanic rock from Merriam Crater in Arizona
 - Same source as the JSC-1 family of simulants (“gold” standard of simulants)
- This 30m X 30m area reproduces the mineralogy, particle shape, reflectivity, glass content and other characteristics of the lunar surface to the maximum practical extent.
- Room exists to enlarge the terrain field and the hazards can be re-configured
 - This image is a “truth map” of the terrain field with better than 2 mm accuracy (Leica MS50 laser scanner)



Moon Express GNC Validation

- Moon Express validated components of their GNC algorithm on three Mighty Eagle flight tests
 - Performed under a Space Act Agreement
 - One test was open loop (Moon Express software running in shadow mode only) on the HAZ03 Flight
 - The 2nd flight was tethered with Moon Express software enabled
 - The 3rd flight was a 21 sec free flight with Moon Express software enabled
- Moon Express software issued pointing commands and had full control of the descent thrusters
 - GNCA maintained control of the ACS thrusters but followed the attitude commands from the Moon Express code
 - Moon Express Code was implemented in cFE modules

Lessons Learned

- Regulator Selection: Mighty Eagle used a classic dome loaded regulator to pressurize the propulsion system. Drift in the setpoint pressure due to ambient temperature change from the time the regulator was set to liftoff caused many operational difficulties.
 - Recommend selection of a regulator that is not so sensitive to temperature changes
- IMU Vibration Isolation: Originally the LN200 IMU was hard mounted to the lower deck. On the first flight the vehicle issued a “Land Now” command prior to liftoff. The navigation solution calculated that the vehicle was outside of the prescribed boundary. This abort was traced to a large change in the IMU accelerometer biases in all 3 axes as the EGC throttled up.
 - The IMU was tested on a shaker table and a quadratic relationship (acceleration bias proportional to the square of the input vibration)
 - The dominant source of the increased bias was attributed to *vibration rectification*
 - Several IMU vibration isolators (commercially available flexible grommets) were tested and the best performing one that reduced vibration rectification to an acceptable level was installed
- Descent Thruster Pulse Width: On Mighty Eagle one of the 3 descent thrusters had a significantly different transient response (both on & off) than the other two.
 - As long as firing commands to the descent thrusters were not “too” frequent the ACS thrusters could manage the disturbance
 - On an early Mighty Eagle flight some of the descent thruster commands were changing every control cycle (50 Hz) which was too much of an attitude disturbance
 - The control law needs to protect against rapid on/off pulsing

Lessons Learned

- Radar Altimeter: The radar altimeter on the Mighty Eagle performed superbly when tested without thrusters firing. When thrusters were firing however, the performance was erratic
 - Likely we could have improved performance by tuning filters and/or using a different radar wavelength.
 - Navigation performance using IMU (LN200) only was adequate so program resources were not spent modifying the radar.
 - Implemented a “gate” on the radar input to the Kalman filter to reject measurements with a large difference from the IMU altitude estimate
- Catalyst Bed Warm-Up: The catalyst bed (silver-nickel plated screens) for each thruster must be heated prior to liftoff. Initial procedure was inadequate.
 - Several short bursts of peroxide is better than a few long duration ones. Flow from a long duration exposure over a cold catalyst bed provides cooling and the catalyst doesn't come up to temperature.
- Core Flight Executive (cFe): The modular software environment from NASA Goddard received high marks from Mighty Eagle software developers

Lessons Learned

- Slosh: A linear slosh model of the cylindrical tanks with upper & lower domes was included in the 6-DOF simulation. Simulations with the linear slosh model showed loss of control.
 - Analysis with linear model showed that 4% slosh damping was needed
 - Peroxide propellant tanks are COPV with 6061 Aluminum liners. No practical way to install ring baffles in the existing tanks
 - Floating polyethylene pellets were tested and provided adequate damping but they are a class 2 material and determined not suitable for long exposure to H_2O_2 .
 - Tank testing in the non-linear range showed that the slosh force saturates at ≈ 10 lbf. Including this saturation force (with abundant safety factor) in simulation showed that control was maintained.
 - Never saw significant slosh dynamics in the flight data
- Propulsion System Maintenance: Believe that premature degradation of the catalyst beds was caused by flushing the system with insufficiently pure DI water.
 - Resolved by using DI water from FMC who supplies peroxide with nitrate ions to prevent damage from chloride. Also reduced the amount of water used to flush the system.

Lessons Learned

- Avionics Thermal Requirements: The integrated avionics box was designed with an ambient temperature limit of 100° F. On hot Alabama days with the vehicle sitting in the sun prelaunch we experienced erratic behavior from the primary avionics unit
 - Specifically, a variety of false error messages from the EGC throttle control motor were generated at high ambient temperatures.
 - Recommend conservative thermal margin on avionics. Applying ambient temperature placards is a significant strain on a test program like this.
- Workforce Development: Many direct and intangible benefits to flight testing programs like Mighty Eagle & Morpheus
 - Mighty Eagle is a **vehicle** with all of the systems any spacecraft has
 - Propulsion, GNC, avionics, flight software, structures, ground software, thermal, S&MA, communications, power, ...
 - It is a great program to rotate young engineers through. Those who work such a project love it and learn things that only hardware can teach

Backup

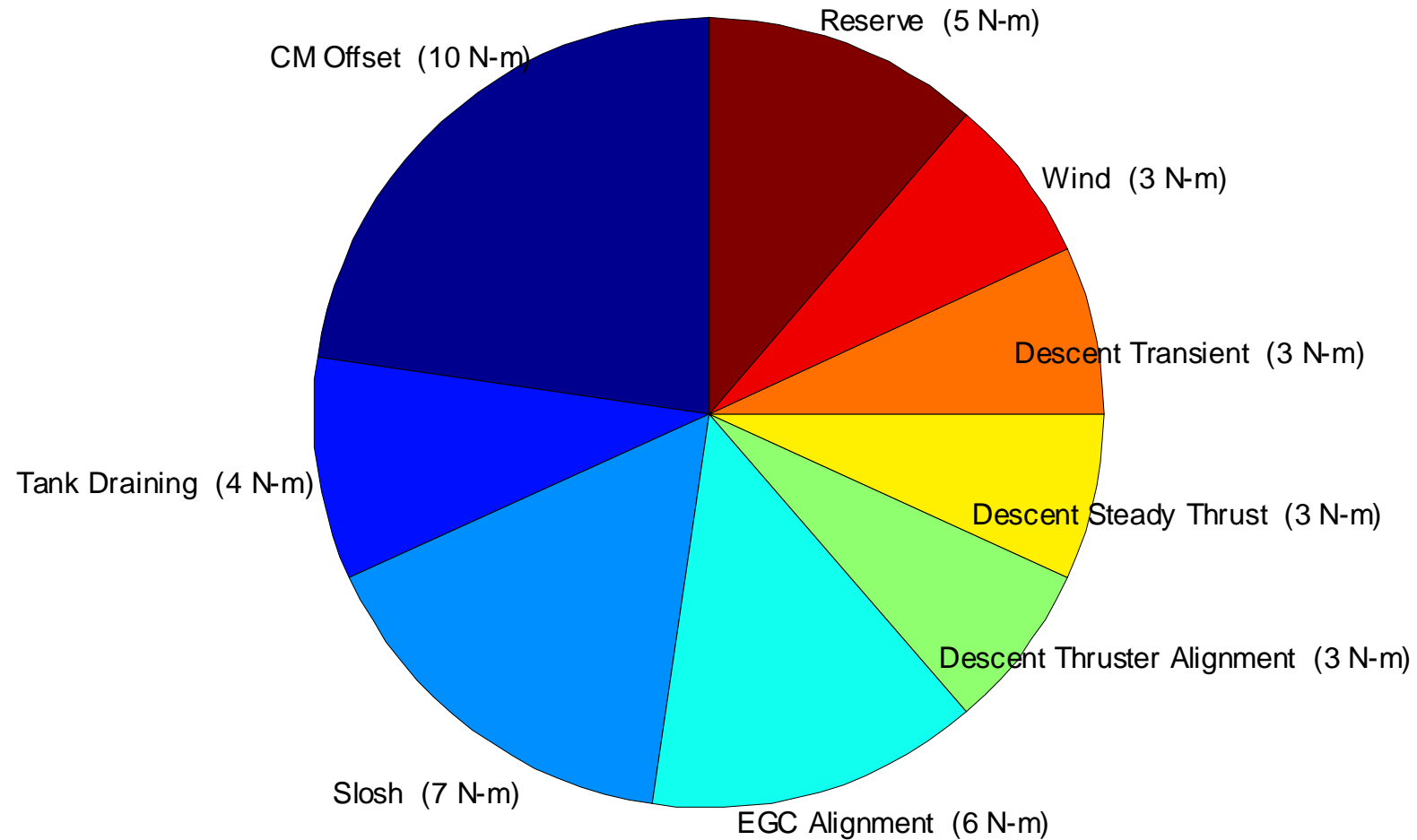
| Flight | Risk Reduction Flights |
|--------|---|
| 1 | LTF02-1, April 5, 2011; Tethered. First flight attempt. Vibration rectification caused measured range to be exceeded and a Land Now abort occurred. IMU was hard mounted to the deck. |
| 2 | LTF02-2, April 14, 2011; Tethered. "Durability" Test. Burp procedure did not adequately warm up thrusters, tethers failed, abort logic didn't latch. |
| 3 | LTF01, June 6, 2011; Tethered. 10 s flight time, 0.5 meter max altitude. Functional checkout and first flight. Vertical drift observed. |
| 4 | LTF02, June 8, 201; Tethered. 17 s flight time, 0.5 meter max altitude. Test of Land Now abort. Vertical drift observed. |
| 5 | LTF03, June 13, 2011; Free Flight. 27 s flight time, 1 meter max altitude. First untethered flight, expansion of flight envelope. Vertical drift observed. |
| 6 | LTF04A, June 16, 2011; Free Flight. 33 s flight, 1 meter max alt. Flight with nearly full fuel, this would be the longest flight for a while. Vertical drift problem corrected. |
| 7 | LTF05, July 6, 2011; Free Flight. 19 s flight, 1 meter max alt. First translation to 4 meters at .5m/s. |
| 8 | LTF06, July 12, 2011; Free Flight. 13 s flight, 5 meter max alt. Expansion of flight envelope and the first descent at two different velocities. Completion of indoor testing. |
| 9 | WTF07, September 16, 2011; Tethered. 12 s flight, .8 meter max alt. First outdoor test and functional checkout after move. Low fuel load caused an early landing. |
| 10 | WTF07B, September 23, 2011; Tethered. 9 s flight, .8 meter max alt. Successful test of Land Now abort at the new location. |
| 11 | WTF08, October 3, 2011; Free Flight. Automatic Land Now abort triggered on takeoff because of static discharge through aluminum standoffs. Thruster side burst disc blew when prop iso opened before purge. |
| 12 | WTF08L, October 6, 2011; Translation. 30 s flight, .5 meter max alt. First outdoor translation to 10 meters at 1m/s. Some steam observed. |
| 13 | WTF09B, October 11, 2011; Translation. Land Now abort sent when heavy vehicle was not able to leave the ground. Some steam observed. |
| 14 | WTF09C, October 14, 2011; Translation with Rotation. 29 s flight, 1 meter max alt. 10 meter translation at 2 m/s with a 90 deg rotation before landing. Only rotation ever performed. Some steam observed. |
| 15 | WTF11, October 17, 2011; Translation at Altitude. 29 s flight, 10 meter max alt. Ascent to 10 meters, 10 meter translation and then descent from 10 meters. Highest flight to date. No steam observed. |
| 16 | WTF11-2, October 21, 2011; Translation at Altitude. 17 s flight, 10 meter max alt. Sluggish takeoff. Aborted because excess steam was observed. |
| 17 | WTF07C, October 24, 2011; Tethered. 10 s flight, .8 meter max alt. Functional checkout after previous aborted flight. New static discharge techniques employed. Excessive steam observed. |
| 18 | WTF11-3, October 25, 2011; Translation at Altitude. 29 s flight, 10 meter max alt. Successful repeat of aborted flight. 10 meter ascent, translation and descent. |
| 19 | WTF15, October 31, 2011; "Flight for Hope" event. Lunar Descent Simulation. 27 s flight, 30 meter max alt. Ascent to 30 meters, lateral descent, null lateral velocity and descend to ground. Excessive steam observed. |
| 20 | WTF18, November 2, 2011; Bowtie. 17 s flight, 10 meter max alt. Attempt to fly bowtie shaped flight ended with abort when the vehicle underperformed. EGC refurb followed. |
| 21 | WTF07-2, Nov 17, 2011; Tethered. 13 s flight, .8 meter max alt. Tethered functional checkout after EGC refurbishment. Little steam. |
| 22 | WTF11-4, Nov 18, 2011; Translation at Altitude. 29 s flight, 10 meter max alt. Repeat of WTF11 flight profile with refurbished EGC. Charlie Bolden observed. |

| Flight | Summary of AR&C Flights |
|--------|--|
| 23 | ARC01, July 17, 2012; Tethered. 14 s flight time, 0.8 meter max altitude. Functional checkout. EGC throttle motor errors. |
| 24 | ARC01-2, Aug 2, 2012; Tethered. Re-do of previous flight. 14 s flight time, 0.8 meter max altitude. Increase understanding of temperature dependent EGC throttle motor errors. |
| 25 | ARC02, Aug 8, 2012; AR&C Open Loop. 32 s flight time, 10 meter max alt. 10" diam circular targets. Only a few target pixels where "white enough" to meet the binarization threshold. No AR&C solutions were generated. Noted dirty lens. |
| 26 | ARC03, Aug 16, 2012; AR&C Closed Loop. 32 s flight, 10 meter max alt. 9 AR&C solutions were generated. Image processing parameters modified for this flight. |
| 27 | ARC04, Aug 28, 2012; AR&C Open Loop. 36 s flight, 30 meter max alt. New target (24" diam circles). 10 AR&C solutions were generated. |
| 28 | ARC05, Sep 5, 2012; AR&C Closed Loop. 36 s flight, 30 meter max alt. 11 AR&C solutions generated. Culmination of AR&C testing. |
| 29 | ARC01A, Oct 19, 2012; Tethered. 10 s flight, 0.8 m alt. Test of "Land Now" in GNCB with descent rate a function of altitude. "Land Now" issued at $t \approx 9.8$ seconds. |
| 30 | ARC06, Oct 25, 2012; Envelope expansion flight (higher, faster, longer). 43 s flight, 51 meter max alt, ascend at 6 m/s. Loaded 114.86 kg of propellant. |
| 31 | ARC01A-2, April 10, 2013; Tethered. 14 s flight, 0.8 m altitude. Change to lightweight legs. Moved GoPro cameras to adjust CG. |
| 32 | ARC07, April 19, 2013; SLI (Student Launch Initiative) demonstration. 34 s flight, 30 meter max alt. First ascent with downrange translation component (which will be needed for upcoming hazard avoidance flights). |

| Flight | Summary of Hazard Avoidance Flights |
|--------|--|
| 33 | HAZ01, Aug 30, 2013; Tethered, 0.8 meter altitude hover with a 14 s flight time. Functional checkout after winter storage, EGC refurbishment, mass property changes (laptop, stereo camera) and new hazard avoidance software. Systems performed well. |
| 34 | HAZ02, Sept. 4, 2013; Planned translation over the terrain field at 20 meters altitude. Flight software issued a "Land Now" command at $t \approx 0.88$ seconds because the measured EGC throttle position error was $> 10\%$ for 10 samples. Believe that limit switch bouncing at 100% throttle caused the EGC position error. Changed max EGC command from 100% to 95% to avoid this problem in the future. |
| 35 | HAZ02-2, Sept. 16, 2013; Translation over the terrain field at 20 meters altitude, 38 second flight. Significant amount of dust was generated. Good stereo images impossible with this much dust. Landed 7.0 meters from target (largest deviation seen to date). |
| 36 | HAZ03, Sept. 20, 2013; Translation over the terrain field at 25 meters altitude, 38 second flight. Terrain field was watered to suppress dust. Flew with Moon Express software in shadow mode. |
| 37 | HAZ02-3, Sept. 26, 2013; Repeat flight #3 (20 meter translation over terrain field) with wet terrain field to suppress the dust. |
| 38 | HAZ05, Oct. 24, 2013; Planned diagonal landing approach from 30 to 20 meters altitude (descend and translate at 1 m/s from 30 meters). Low propulsion system pressures resulted in significantly reduced performance (only reached an altitude of 23 meters, planned for 30 meters). Excessive atmospheric steam generated preventing the acquisition of any useful stereo images ($T \approx 40^\circ\text{F}$, relative humidity $\approx 68\%$). |
| Flight | Summary of Moon Express Guidance Flights |
| 39 | MEG01, Nov 14, 2013; Tethered, 0.8 meter altitude hover with a 14 s flight time. Initial checkout of Moon Express Guidance (MEG) software. Hovered at ≈ 0.4 m altitude, not the planned 0.8 meters. Relatively large roll ACS on time. Had one 20 ms Descent thruster pulse. NanoLaunch IMU on-board. |
| 40 | MEG02, Nov 25, 2013; Free flight (no tethers) hover at 3 m altitude, 21 s flight time. MEG software tuned after analysis of flight 1 data. Roll ACS on time much improved from (reduced from $\approx 40\%$ to $\approx 20\%$). Hover altitude closer to the altitude command than for flight 1. NanoLaunch IMU on-board. |

Total of 40 Test Flights (14 of them Tethered)

Mighty Eagle Torque Budget



Total Budget of 44 N-m

- Assuming 10 lbf (44.5 N) ACS Thrusters
- Moment arm = 0.76 m